ASSESSMENT OF 2006 AND 2007 DROUGHT PATTERNS IN THE VEGETATION
DROUGHT RESPONSE INDEX ACROSS NEBRASKA

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ABSTRACT
The Vegetation Drought Response Index (VegDRI), a hybrid geospatial drought indicator and monitoring tool, provides timely drought severity information with relatively higher spatial resolution (1 km²) than traditional drought monitoring maps. The VegDRI models integrate climate-based drought index data, satellite-based vegetation index information, and several biophysical parameters. During the 2008 growing season, VegDRI was produced in near-real time for 22 states in the central and western United States. Coverage will expand across the conterminous United States in 2009. Validating the results of large-area, operational monitoring tools like VegDRI requires extensive ground truth information across space and time, and to date, only a limited number of assessments of this index have been conducted. This study initiates a comprehensive assessment of historical VegDRI based on a comparison with crop yields to better characterize the accuracy and performance of VegDRI for agricultural drought monitoring. This assessment evaluated drought severity information provided by VegDRI for Nebraska in 2006 and 2007 identified using crop and irrigation masks. Moderate to severe drought conditions occurred during 2006 and very little drought occurred in 2007. Spatial and statistical comparisons of VegDRI and U.S. Department of Agriculture (USDA) crop yield data were conducted for both years. In this study, comparisons were restricted to Nebraska’s two predominant crops, corn and soybeans. Non-irrigated row crops were analyzed separately. Preliminary results showed that non-irrigated corn yields had a stronger relationship to late-season VegDRI than non-irrigated soybeans. Moderate drought impacts in 2006 were also highlighted by this analysis.

INTRODUCTION
Monitoring drought is challenging because of the large temporal and spatial variability of drought events. Monitoring techniques need to be adapted to capture the time, location, and sector-specific characteristics of drought. The Vegetation Drought Response Index (VegDRI) characterizes agricultural drought (Brown et al., 2008). VegDRI is considered to be a hybrid model because three distinct types of data inputs are integrated into the index’s calculation: 1) climate-based drought indices, 2) optical satellite observations, and 3) biophysical descriptors of the environment. Models are trained on historical data series and then implemented in near-real time on current climate and satellite observational data to produce a 1-km² resolution VegDRI map.
Operational near-real time VegDRI maps are currently made available to users via two online mapping services. An interactive map server is hosted by the USGS (http://gisdata.usgs.gov/website/Drought_Monitoring/viewer.php) where VegDRI can be viewed in combination with additional geospatial data layers. The National Drought Mitigation Center also hosts VegDRI maps and tabular summary data (http://www.drought.unl.edu/vegdri/VegDRI_Main.htm) and collects feedback regarding the index’s relative accuracy from a variety of evaluators.

The VegDRI model is based on the self-calibrated Palmer Drought Severity Index (PDSI; Palmer, 1965, Wells et al., 2004) as a dependent variable. The PDSI, calculated based on a simple supply-and-demand water balance model, builds on the temperature and precipitation history for a location. In the self-calibrated PDSI, empirical constants and duration factors in the PDSI computation are dynamically calibrated to local characteristics. This adjustment was designed to keep the original intentions of Palmer’s (1965) drought index intact while improving the spatial comparability of PDSI so that extreme dry and wet events occur approximately two percent of the time (Wells et al., 2004).

In past studies, the PDSI has shown moderate to strong relationships with crop yields (Easterling et al., 1988, Meyer et al., 1991, Quiring and Papakryiakou, 2003, Scian and Bouza, 2005 Wu et al., 2004, and Mavromatis, 2007). These studies have related the PDSI calculated at weather stations with wheat and corn yields for surrounding administrative units across different spatial and temporal extents. The self-calibrated PDSI was developed in 2004, and because it is relatively new, fewer results have been published using this index (Mavromatis, 2007). Quiring and Papakryiakou (2003) carried out a geographically extensive performance analysis of four agricultural drought indices, including the PDSI, to determine the most appropriate index for monitoring agricultural drought related to spring wheat yields across the Canadian prairies.

This study outlines a comparison of VegDRI geospatial model results for Nebraska to observed corn and soybean yields (2006 – 2007) using several goodness-of-fit measures that include the coefficient of determination ($R^2$), the index of agreement ($d$), and the Nash-Sutcliffe coefficient of efficiency (NSCE; Nash and Sutcliffe, 1970). Each measure has specific strengths and weaknesses for understanding model performance; therefore, a suite of measures provides a broader and more comprehensive basis for statistical assessment (Willmott, 1984). Figure 1 shows late summer 2006 and 2007 VegDRI and the U.S. Drought Monitor (USDM) maps (Svoboda et al., 2002) for Nebraska. The maps show moderate to severe drought conditions in 2006. In 2007, the conditions approached normal across much of the state, except for the Panhandle region (northwest), which experienced moderate to severe drought.

BACKGROUND

Prior research has suggested that crops exhibit sensitivity to drought during different phenological stages. Corn, during the silking stage which commonly occurs during the first half of July in Nebraska (Wu et al., 2004), is especially drought sensitive. Corn also exhibits risk to drought during the reproductive stage in early August, which can result in yield reductions. Soybeans are known to be less sensitive to drought than corn; however, drought stress in the later stages (August and September) of the growing season can initiate senescence in the soybean plants and thus limit soybean yields (Brevedan and Egli, 2003).

This study examines the usefulness of VegDRI models and data as an agricultural drought indicator by evaluating the relationship between VegDRI and crop yields during the critical periods affecting each crop’s yield. The current analysis also divided the irrigated and rainfed areas in Nebraska for both crops in 2006 and 2007 to consider these two widely applied management practices under which these crops are grown across the state. Three goodness-of-fit measures were used to determine the strength of the relationship between VegDRI and crop yield data.
Figure 1. VegDRI and U.S. Drought Monitor maps for summer 2006 and 2007.
The coefficient of determination ($R^2$) is widely used to determine the degree to which two variables are related and explains the fraction of variability in $y$ that can be explained by the variability in $x$. The equation is

$$R^2 = \frac{SSTotal - SSRes}{SSTotal} = 1 - \left(\frac{SSRes}{SSTotal}\right)$$

where the SSTotal is the total sum of squares of the data and SSRes is the residuals of the sum of squares.

The index of agreement ($d$) is the ratio between the mean square error (MSE) and the potential error (PE) and measures the degree to which the observed data are approached by the predicted data. It overcomes the insensitivity of correlation-based measures (e.g., $R^2$) to differences in the observed and predicted means and variances (Willmott, 1984). This index lies between 0 and 1, where 0 indicates no agreement and 1 indicates perfect agreement for data pairs. The measure $d$ is calculated by

$$d = \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (|P_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

where $O_i$ is the observed data and $P_i$ is the predicted data.

The Nash-Sutcliffe coefficient of efficiency (NSCE) was the third index that was used in this analysis. The NSCE includes the mean-square-error term and is suitable for the assessment of model goodness-of-fit (Legates and McCabe, 1999), and unlike the coefficient of determination ($R^2$), the NSCE accounts for model errors (Nash and Sutcliffe, 1970). The closer the value of the NSCE is to 1, the better the overall fit of the model. The NSCE is calculated by

$$NSCE = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}$$

where $P_i$ is the predicted variable, $O_i$ is the observed variable, $\bar{O}$ is the observed mean, and $n$ is the number of variables.

**METHODS AND DATA**

A pixel-level comparison between 1-km$^2$ resolution VegDRI maps and crop yields was not possible without field-specific crop yield data. However, we used county-level crop yield data available from the USDA NASS (USDA NASS, 2008b) and implemented the following steps for this study.

**County Crop Yield Data**
For this assessment, we employed county-level crop yield data from USDA-NASS for 2006 and 2007 (USDA NASS, 2008b). To eliminate the upward linear trend in a time series of yields due to advancements in agricultural technology and crop hybrids, the yield data were detrended by regressing the annual county yields against the year. Forty-three years of historical yield data (1965–2007) were used to detrend the county yield statistics. The detrended yields were also normalized so that all yields are comparable. A detrended normalized yield index (DNYI) was calculated for four crop/land use type combinations (corn—rainfed, corn—irrigated, soybeans—rainfed, and soybeans—irrigated). Figure 2 shows a time-series plot of original yields and detrended yields for Adams County in Nebraska with the 2006 and 2007 study years highlighted. The effects of the normalization and detrending are more obvious in the early half of the time series; however, the negative 2006 DNYI highlights how the DNYI may show the potential influence of drought on yield during this year.
County-level Crop-specific VegDRI Methodology

Three masks were used to constrain the specific pixels in the VegDRI maps used for statistical comparison with county-level USDA crop yield data. These masks are 1) corn and soybean masks for 2006 and 2007, 2) an irrigation status mask, and 3) a county mask. These three masks allowed us to summarize the VegDRI for the specific crop and irrigation status to match the USDA yield statistics.

Crop Type Masks for 2006 and 2007

The crop type mask for Nebraska involved several steps. First, we generated a general agriculture mask from the 2001 National Land Cover Database (NLCD) (Homer et al., 2004). Two categories were included (class 81: Cultivated Crops, and class 82: Pasture/Hay) and all other areas were excluded from further analysis. These agricultural pixels were then identified as a specific crop type for both study years from the 2006 USDA Cropland Data Layer (CDL; USDA NASS, 2007) and the 2007 CDL (USDA NASS, 2008a) for Nebraska. For each crop type mask, the respective CDL data were summarized to 1 km² using a 60 percent threshold. Each 1-km pixel included in the NLCD-derived general agriculture mask was labeled as corn, soybeans, other crop, and non-crop when greater than 60 percent of the 1-km² pixel footprint was occupied by one of these classes. The 60 percent threshold was selected to ensure that the crop yield comparison would be made to pixels with relatively homogenous crop cover (dominated by corn or soybeans). We experimented with higher (and therefore more rigorous) thresholds (e.g., 75 percent), but they substantially reduced the number of counties included in the crop comparison.

Irrigation Status Mask

In this step, each 1-km² pixel from the corn and soybean masks was then labeled as irrigated or non-irrigated based on a Nebraska 2005 Landsat-derived irrigation map (Dappen et al., 2007). A corn or soybean pixel was labeled as irrigated if greater than 50 percent of the 1-km pixel’s area was designated irrigated based on the Nebraska irrigation map. Otherwise, it was labeled non-irrigated. A simple 50 percent threshold was used to set a majority rule criteria for irrigation status.

Figure 2. Time series plots of original yields (orange line) and DNYI (blue line) for Adams County, Nebraska. Red circles highlight the DNYI in 2006 and 2007 study years.
For final calculation, a county polygon was applied over the irrigated and non-irrigated corn and soybean masks, and the median VegDRI value was calculated for the all pixels in a county corresponding to irrigated corn, non-irrigated corn, irrigated soybeans, and non-irrigated soybeans. Counties with fewer than 25 pixels in a given crop mask were eliminated from further analysis.

VegDRI Periods
Calendar dates selected for VegDRI/USDA crop yield comparisons for 2006 and 2007 are shown in Table 1. Specific dates for the crop comparisons were selected for critical periods during the growing season during which the environmental conditions strongly influence each crop’s yield. In addition, we consulted archived issues of the 2006 and 2007 Weekly Weather and Crop Bulletins (http://www.usda.gov/oce/waob/jawf/wwcb.html), prepared jointly each week since the 1970s by the National Oceanic and Atmospheric Administration and the USDA, to help identify the most appropriate dates for each study year. Crop Progress and Condition tables present percentages by state of the stages of various crops, including corn and soybeans. For example, the first half of July corresponds with the timing for silking in corn in Nebraska (Wu et al., 2004). The Weekly Bulletins (http://www.usda.gov/oce/waob/jawf/wwcb.html) for July 17, 2006, indicated that by July 15, 57 percent of the corn crop in Nebraska had completed its silking stage. Similar information was acquired from the Bulletins for all of the above dates for both crops. In soybeans, water deficits in the middle to late productive stages (i.e., August and September) will hasten the plant’s maturation and thus reduce crop yield. Late summer dates were selected for soybeans for this reason.

<table>
<thead>
<tr>
<th>Crop yield</th>
<th>2006 VegDRI date</th>
<th>2007 VegDRI date</th>
<th>Estimated crop phenological stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-irrigated corn</td>
<td>July 11</td>
<td>July 16</td>
<td>Silking</td>
</tr>
<tr>
<td>Non-irrigated corn</td>
<td>August 22</td>
<td>August 27</td>
<td>Reproduction</td>
</tr>
<tr>
<td>Non-irrigated soybean</td>
<td>August 22</td>
<td>August 27</td>
<td>Pod setting</td>
</tr>
<tr>
<td>Non-irrigated soybean</td>
<td>September 5</td>
<td>September 10</td>
<td>Pod filling</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

VegDRI Evaluation
Table 2 contains the performance statistics (indices of agreement) for county-based median VegDRI compared to corn and soybean yields during two stages of crop development. Of the two crops and the two development stages, the VegDRI results in the second half of August correlated the best with the detrended yield for corn ($R^2 = 0.48$), agreed well with the observed yields ($d = 0.82$) and had the highest NSCE (NCSE = 0.51).

<table>
<thead>
<tr>
<th>Crop type</th>
<th>Agreement Indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
</tr>
<tr>
<td>Non-irrigated corn (July first half)</td>
<td>0.44</td>
</tr>
<tr>
<td>Non-irrigated corn (August second half)</td>
<td>0.48</td>
</tr>
<tr>
<td>Non-irrigated soybean (August second half)</td>
<td>0.22</td>
</tr>
<tr>
<td>Non-irrigated soybean (September first half)</td>
<td>0.28</td>
</tr>
</tbody>
</table>
**Corn Comparison**

Scatterplots show the VegDRI and DNYI for counties (46 in 2006 and 38 in 2007) considered in the corn yield comparisons (Figure 3). The $R^2$ results (0.48) for corn in the second half of August compared favorably to earlier studies. Quiring and Papakryaihou (2003 study results for wheat were 0.27 (related to PDSI) involving yield data from 39 years of observations.

![Non-irrigated corn](image1)

![Non-irrigated corn](image2)

Figure 3. Median VegDRI and county non-irrigated corn yield scatterplots. 2006 results are in red, and 2007 results are in blue.

**Soybean Comparison**

The soybean yield comparison results are shown in Figure 4 for counties (35 in 2006 and 15 in 2007). The VegDRI had a weaker relationship with soybean yields in both crop stages analyzed compared to corn. Based on this temporally limited analysis, the results suggest that VegDRI may not be a good discriminator of agricultural drought effects on soybeans, but further research is needed. We did not find prior publications exploring the relationship of the PDSI and soybean production.
Figure 4. Median VegDRI and county non-irrigated soybean yield scatterplots. 2006 results are in red, and 2007 results are in blue.

**VegDRI and DNYI trends**

To determine whether consistent trends (positive and negative) were exhibited by the VegDRI and yield data, we show a simple matrix comparison of each yield-VegDRI pair (Tables 3–6). These tables show counts describing the sign consistency of the data for each county in the assessment [i.e., positive (negative) DNYI to positive (negative) VegDRI]. The paired signs of DNYI and VegDRI were counted for the 84 corn county results (Tables 3 and 4). The results from both time periods stay consistent, and 67 of 84 county observations exhibited matching sign relationships. The cell (Tables 3 and 4) representing positive DNYI and negative VegDRI for corn represents the greatest confusion in the results and might result in more serious drought assessments related to corn yields when relating VegDRI to corn yields under moisture stress.
Table 3. Comparison matrix for non-irrigated corn (1st half of July, 2006 and 2007)

<table>
<thead>
<tr>
<th>No. of counties</th>
<th>VegDRI &lt;= 0</th>
<th>VegDRI &gt; 0</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNYI &lt;= 0</td>
<td>33</td>
<td>5</td>
<td>38</td>
</tr>
<tr>
<td>DNYI &gt; 0</td>
<td>12</td>
<td>34</td>
<td>46</td>
</tr>
<tr>
<td>Total</td>
<td>45</td>
<td>39</td>
<td>67/84</td>
</tr>
</tbody>
</table>

Table 4. Comparison matrix, non-irrigated corn (2nd half of August, 2006 and 2007)

<table>
<thead>
<tr>
<th>No. of counties</th>
<th>VegDRI &lt;= 0</th>
<th>VegDRI &gt; 0</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNYI &lt;= 0</td>
<td>33</td>
<td>5</td>
<td>38</td>
</tr>
<tr>
<td>DNYI &gt; 0</td>
<td>12</td>
<td>34</td>
<td>46</td>
</tr>
<tr>
<td>Total</td>
<td>45</td>
<td>39</td>
<td>67/84</td>
</tr>
</tbody>
</table>

The risk of interpreting exaggerated drought severity effects in VegDRI appears to be greater for soybeans where the paired signs of DNYI and VegDRI (Tables 5 and 6) show less consistency than the corn results. More than half (26 of 50) of the county observations showed positive DNYI related to negative county VegDRI results. However, more analysis is recommended.

Table 5. Comparison matrix, non-irrigated soybeans (2nd half of August, 2006 and 2007)

<table>
<thead>
<tr>
<th>No. of counties</th>
<th>VegDRI &lt;= 0</th>
<th>VegDRI &gt; 0</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNYI &lt;= 0</td>
<td>9</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>DNYI &gt; 0</td>
<td>26</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>36</td>
<td>14</td>
<td>23/50</td>
</tr>
</tbody>
</table>

Table 6. Comparison matrix, non-irrigated soybeans (1st half of September, 2006 and 2007)

<table>
<thead>
<tr>
<th>No. of counties</th>
<th>VegDRI &lt;= 0</th>
<th>VegDRI &gt; 0</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNYI &lt;= 0</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>DNYI &gt; 0</td>
<td>26</td>
<td>14</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>36</td>
<td>14</td>
<td>24/50</td>
</tr>
</tbody>
</table>

**CONCLUSIONS AND NEXT STEPS**

Since drought is only one factor affecting crop yield (other factors include management practices, hail, flooding, and insect infestations), we are not overly surprised by these statistical results. VegDRI is primarily an indicator of drought intensity and not intended as a direct indicator of crop yield; however, the trends in VegDRI should follow general trends in crop yields. In addition, this analysis was based on only two years, and expanding further analysis to include broader variability in climate and drought conditions ought to improve crop yield comparison results. Considering the results of these comparisons between non-irrigated corn and soybean VegDRI summaries and crop-specific DNYI, the best relationship was for non-irrigated corn during the reproductive stage. However, the statistical results for corn in the early part of July compared to the latter part of August are very similar. During the second half of August, the range in the county VegDRI looks to be comparatively reduced at this time as well, meaning there was less variability in VegDRI later in the season in 2007. More investigation is required to determine whether VegDRI for certain crop types has reduced variability at different phenological stages.

For non-irrigated soybeans, the first half of September corresponds to the typical timing of soybean pod-filling, which is an important determinant of crop yield. However, the VegDRI calculated for non-irrigated soybeans had a much less significant relationship with soybean yields than it did with corn yields over these two years ($R^2 = 0.224$ and $R^2 = 0.277$, for the second half of August and the first half of September, respectively). This result is supported by prior research that suggests that soybeans are less vulnerable to drought than corn (Wu et al. 2004). VegDRI
does not appear to be an appropriate tool for assessing drought effects on soybean yield. Again, further research will help determine whether this is the case.

A complete and comprehensive validation of VegDRI is ongoing and is based on a diverse set of information. Thus, this corn and soybean yield comparison is one component of a broader evaluation. Other components include a spatially applied model cross-validation, comparisons with multitemporal clip plot data of several biophysical vegetation characteristics, and comparisons with time-series soil moisture observations from climate networks. In this evaluation, the trends in VegDRI were somewhat consistent with the trends seen in corn and soybean yields. This analysis, while limited to one state, two crop types, and two years, provided encouraging results and a path forward to further assessment of VegDRI. Further crop yield comparisons will be made for additional crops, geographic areas, and a wider series of years. A comprehensive validation of VegDRI as an agricultural drought assessment tool will also require other multiyear observations that are environmental descriptors of agricultural drought (e.g., soil moisture and vegetation biomass changes) collected across the growing season for a considerable number of sample locations.

REFERENCES


